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SPACE NUCLEAR PROPULSION FUEL AND MODERATOR DEVELOPMENT PLAN CONCEPTUAL TESTING REFERENCE DESIGN

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As future National Aeronautics and Space Administration (NASA) missions aim for destinations farther out into the solar system, Space Nuclear Propulsion (SNP), and in particular Nuclear Thermal Propulsion (NTP), is the only feasible near-term technology able to provide specific impulses of 900 seconds or greater and thrust in the range of tens of thousands of pounds. To maximize the success of the SNP program as a whole, a Fuel and Moderator Development Plan (FMDP) was created to mature mission critical technology, such as the reactor fuel form and moderator material. This paper details the conceptual testing reference design that provides the basis for the FMDP for future design and testing activities to meet NASA's goals.

I. INTRODUCTION

The SNP FMDP activities are coordinated by NASA and the Department of Energy (DOE) and include the following requirements to develop a subscale nuclear engine that demonstrates the viability of the NTP propulsion system and is scalable to the Mars mission needs:

1. Develop a High Assay-Low-Enrichment Uranium (HA-LEU) solid fuel form that can provide reactor exit temperatures greater than or equal to 2700 K.

2. Develop a moderated reactor conceptual design which includes, but is not limited to, a moderator block concept.

3. Develop a sub-scale, non-nuclear engine for early testing that leverages the benefits from conventional system development processes with the infusion of advances in nuclear fuel and reactor technology development.

This paper incorporates the initial summary issued via technical note [1] and further summarizes the design assessments completed. The reactor subsystem (RSS) conceptual testing reference design activities support decisions regarding technology development and the integrated fuel assembly in the moderator block unit cell test at the Idaho National Laboratory (INL) Transient Reactor Test (TREAT) facility. While the scaled configuration tests with a fuel assembly/moderator assembly in hydrogen is further out in calendar year 2022/2023, efforts made in advance assist with building toward the capstone tests.

I.A. FMDP Ground Rules

The proposed FMDP RSS testing reference design concept is based on the following ground rules:

1. The reactor uses a HA-LEU Uranium Nitride (UN) fuel kernel embedded in zirconium carbide (ZrC), referred to as cercer fuel, or molybdenum/tungsten (Mo/W), referred to as cermet, matrix material in a moderator block arrangement.

2. The gas (hydrogen) nozzle chamber temperature must be sufficient to reach an engine specific impulse (I_{sp}) of 900 sec. This is analogous to an approximate fuel channel exit gas temperature of ~2700 K.

3. The engine thrust is in the range of 12,500 to 15,000 lb_f.

4. The dry RSS mass limit is ~3,800 kg. This does not include turbomachinery, nozzle or external shielding mass allocations. This mass limit does include the necessary internal shielding.

5. The fuel elements are circular in shape with internal cooling channels.

Fabrication of the cermet fuel form is expected to be performed via spark plasma sintering (SPS) furthering development of the processing parameters developed under Game Changing Development (GCD). A thin refractory metal coating is applied to the UN kernel to protect the kernel from exposure to the atmosphere during handling as well as to promote bonding with the matrix material during fabrication of the composite fuel form. BWX Technologies, Inc. (BWXT) has previously manufactured W-coated UN particles. These particles will be tested in the very near future as part of the SNP FMDP test plans. The leading fuel particle proposed for the SNP cercer fuel is a UN kernel with a ZrC protective coating. The primary purpose of the coating is to prevent or slow carbon interaction with the UN kernel during operation [2][3]. Investigating fuel performance will be a major focus of future FMDP design activities.

II. DESIGN DESCRIPTION

The RSS conceptual testing reference design conforms to the typical NTP reactor arrangement, utilizing a neutron reflecting material surrounding the active core region using control drums lined with a neutron absorbing material and flow plenums for directing coolant flow through regions within the RSS. The FMDP conceptual testing reference design is available within the registered content on the NASA Technical Reports Server (NTRS) [4].

The active core region utilizes a moderator block design. Several historical reactor designs relied on slab moderator configurations. For example, the Experimental Beryllium Oxide Reactor (EBOR) utilized cylindrical assemblies inserted into blocks of beryllium oxide (BeO) [5]. The Heat Transfer Reactor Experiment (HTRE) design utilized solid moderator blocks of zirconium-hydride (ZrH) in a similar arrangement [6]. The moderator block configuration allows for more efficient neutron moderation and reduced intra-element power gradients, allowing for a significant increase in exit gas temperature.

The moderator material selection is a multi-faceted, inter-disciplinary trade-off between cost, manufacturability, mechanical integrity, reactor weight and active core volume. When all of these factors are considered, a ZrH moderator block is recommended. The ZrH moderator material allows for significantly reduced core diameter, which minimizes the reactor radial reflector and support structure masses. With the hydride moderator block design concepts, the better moderating properties relative to other solid moderators produce improvements in the U235 fission cross section and capture to fission ratio, and decrease in leakage [10]. These improvements offset any potential mass penalties due to a higher material density and parasitic loss to hydrogen absorption due to the optimized neutron economy. The choice of a ZrH moderator, therefore, also reduces the required amount of HA-LEU UN fuel, a valuable resource, resulting in improved sustainability.

Two potential fuel forms are proposed for the testing reference design. The first fuel form is cermet, utilizing a Molybdenum (Mo) 30 weight percent (wt%) W alloy (Mo:30W) which has been previously utilized in NASA GCD program efforts and several academic research papers [7][8][9]. The second fuel form is a cercer fuel with a ZrC matrix. While each fuel type has advantages and disadvantages, both must follow a similar development progression to ultimately be integrated as part of the SNP engine. The moderator block architecture improves cost and risk management by decoupling RSS development from fuel and moderator development. While core loading patterns and coolant channel element geometries may vary between fuel forms, the outer diameter of the fuel element is constrained such that either fuel form can be used in the same RSS design. This is made possible by fitting the fuel element(s) into a cartridge-like fuel assembly, which is then placed within the moderator block region to assemble the reactor core. This allows for the design of the RSS to be adaptable to multiple fuel forms and mature independently of the fuel form.

Cooling channels are directly integrated into the moderator block to ensure the temperature limits of ZrH are not violated during engine operation. The coolant in the moderator block enters at the bottom of the core and makes a single pass through the moderator block before recombining with the flow from the radial reflector. The active core region contains 61 fuel assemblies and each fuel assembly contains 91 internal coolant channels. The coolant enters the fuel channels from the top of the reactor and makes a single pass through the fuel assemblies before entering the rocket nozzle chamber.

III. DESIGN ASSESSMENTS

This section contains discussion on a selected sub-set of analyses performed on the conceptual testing reference design including neutronic, thermal hydraulic, and stress assessments.

III.A. Neutronics

BWXT's internally developed machine learning based optimization tools were leveraged to provide a conceptual reactor design that met all of the required performance criteria, while in accordance with the FMDP ground rules. The continuous energy Monte-Carlo particle transport code MCNP6.2 was used to conduct all neutronic analysis.

Energy deposition distribution by reactor component was considered for both core designs. The values include both neutron and photon direct energy deposition. The results demonstrate that the majority of the energy produced is directly deposited in the fuel element. One notable difference between the two designs is that the cercer design has 1.31% more energy directly deposited outside the fuel elements.

Additional optimization was performed to flatten the radial power profile for both designs to achieve maximum thermal performance and minimize the pressure drop from orificing.

The profiles were tailored by adjusting the fuel to matrix volume ratio in each fuel assembly, with an upper limit of 65 volume percent (vol%) of fuel particles. The fuel kernel uranium enrichment was kept constant at 19.75 wt% ^{235}U to minimize parasitic absorption in ^{238}U. The cermet fueled core was able to obtain a smoother radial power profile, with a maximum radial peaking

factor of 1.02 and a minimum of 0.96. The cercer core also achieves a satisfactory radial power peaking, with a maximum of 1.03 and a minimum of 0.97.

Values were determined at beginning of life (BOL) hot full power operational conditions, with the drums rotated 120 degrees from fully inserted. It should be noted that the cores are slightly super critical at a 120-degree drum rotation. This reserves some excess reactivity for future design trade-offs. The direct energy deposition distribution parameters do not change much over the expected reactor lifetime. The integral drum worth represents the total change in reactivity from rotating the drums from their completely inserted position to a completely removed position.

The H:^{235}U ratio for cercer was 306:1 and cermet 41:1, which accounts for the hydrogen present in the moderator block and excludes any hydrogen present in the coolant channels.

One of the major advantages of the moderator block design over discrete moderator elements is an improved neutron economy. Neutron economy ties to the material in which the neutrons are being absorbed and their proportional worth of the total available reactivity for a RSS. The ^{235}U worth fraction of neutron economy must be above 1.00 for reactivity criticality and a viable core design. The moderator block configuration provides reactivity margin, which can be used to improve thermal hydraulic performance and reduce reactor mass.

III.B. Thermal and Mechanical Assessment

The thermal and mechanical analyses of the hot fuel assembly and surrounding moderator unit cell was a primary focus during the conceptual testing reference design phase due to the peak fuel-to-moderator coolant temperature differences, which could lead to thermally and mechanically conservative results for the entire reactor core. Required changes to the entire RSS could be inferred from the performance of this assembly.

The assessment of the hot fuel assembly was performed using ANSYS Mechanical APDL finite element analysis (FEA) software [11] to evaluate a series of 2D planar models. Each planar model represented an 11 mm length of the hot assembly with the geometry and mesh. The thermal load and boundary conditions for each model were determined using a combination of analytic methods that translated the FMDP ground rules (Section I.A.) and direct energy depositions into plant power balance data, which were then used in combination with axial and radial power profiles to calculate channel-and-elevation-specific fluid temperatures and convection coefficients.

The fuel and moderator assembly thermal analysis considered axial and radial power peaking factors. The effects of intra-element peaking were not included, but are recommended to be included in future work. Hydrogen gaps between fuel assembly components were included in the analysis. Although considered stagnant gaps, the effects of conduction, thermal radiation and changes to gap size were included in the thermal analysis. The effect of natural convection within these gaps was shown to be negligible and was therefore not included. The hot channel temperature profiles for the cermet and cercer designs were determined.

Both the cercer and cermet peak fuel temperatures are under the design temperature target of 2850 K. The peak moderator temperature for the cermet concept is below the ZrH temperature limit. The peak moderator temperature for the cercer concept is also below the ZrH temperature limit. Heat transfer between the fuel assembly and moderator is considered in the calculation of thermal boundary conditions. Extrapolating from the hot assembly analysis, the estimated heat conducting to the moderator for the entire core is 5.64 MWt in the cermet design and 6.18 MWt in the cercer design. The combination of the greater fuel-assembly-to-moderator heat transfer and direct energy deposition in the moderator cause the higher peak temperatures in the cercer moderator.

A comparative linear elastic steady state structural analysis of both the cermet and cercer concepts was completed. Planar stresses and displacements were calculated using the temperature profiles determined in the thermal analysis. The peak stresses in the insulator, outer wall and moderator are comparable for both fuel assembly concepts. The cermet concepts have higher stresses in the fuel cladding. The stresses in the insulator wall are high relative to the material strength. The stresses in the structural outer wall are reasonable in comparison to the material capabilities. Peak moderator stresses indicate the potential for mechanical failure in the moderator block; however better material properties are required for a more accurate evaluation. The peak stresses in the insulator, outer wall and moderator are comparable for all fuel assembly concepts. The largest differences are observed in the fuel meat and cladding where the cermet concepts have higher stresses in the fuel cladding. The CTE mismatch between the cladding and the fuel meat is a significant factor in these stresses.

IV. SUMMARY AND CONCLUSIONS

Two reactor design concepts were developed to support the FMDP: one utilizing a cermet fuel form and the other utilizing a cercer fuel form. Both designs adhere to the FMDP ground rules detailed in this paper and meet the performance requirements. A view of the reactor design is provided in Figure 1.

The supporting neutronic, thermal hydraulic and mechanical analysis demonstrates the viability of both designs and provides valuable insights to inform development and testing to progress technology maturation important for SNP NTP applications. The cercer fuel form needs approximately seven times less HA-LEU, reduced maximum fuel meat stress and is about 400 kg lighter than the cermet fuel form. However, the cermet design leverages a previously manufactured fuel form with a beneficial epi-thermal neutron spectrum. Future work will focus on further study and refinement of the conceptual testing reference design summarized herein, in support of the FMDP development of the cercer and cermet fuel forms for integration in a complete SNP engine.

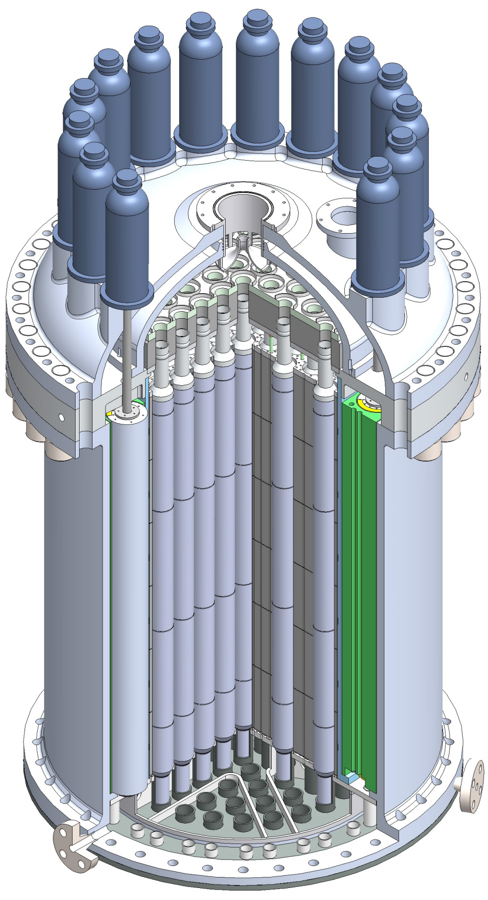

Fig. 1. Reactor subsystem cross section

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